Robotic Brickwork: Towards a New Paradigm of the Automatic

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This contribution characterises the fundamentals of robotic brickwork — where industrial robots are used not only for construction but also as a guiding principle in the design and fabrication process. Featuring six-axis robotic arms that position single bricks according to a precise digital blueprint, robotic brickwork offers a comprehensive new paradigm in building construction: intricate automated assembly methods. Initiated by the Gramazio Kohler Research Group at ETH Zurich, this approach to brickwork offers unique advantages over traditional brickwork approaches: it does not require scaffolding, it is easily scalable and it offers digital integration and informational oversight across the entire design and building process. This contribution considers 1) the advent of robotic brickwork in architecture, 2) research parameters and demonstrations for integrative computational design methodologies and fabrication techniques to enable this process and 3) the architectural implications of integrating these components into a systemic, unifying brickwork construction system. Industrial transfer and full-scale construction are of particular concern.

In robotic brickwork, the combination of a well-established building material, new digital design processes and fabrication techniques allows non-standard assembly to become an increasingly interesting architectural avenue, departing from traditional and labour-intensive manufacturing processes. Indeed, despite strong advancements in digital planning using computer-aided design (CAD) systems, the construction sector is still characterised by a high proportion of manual assembly tasks. Together with the inherently limited flexibility and working areas of conventional computer numeric control (CNC) machinery, this handicaps the field with regards to taking
advantage of the rapidly spreading trend of using complex digital design information directly as input for comprehensively automated construction processes. Here, robotic systems are extremely useful not only can their use lead to significant time savings but their ability to precisely transfer computational design data directly to real-world manufacturing operations can also enable the fully automated construction of non-standard building structures. In particular, their use opens up entirely new possibilities for future brickwork that is not limited by the same constraints — such as, for example, standardised assembly routines — that limit manual assembly processes; its most evident and radical consequences are the ability to digitally oversee and control a large number of elements and, most importantly, the ability to freely position these elements in space. In order to address these potentials, the Gramazio Kohler Research Group at ETH Zurich started comprehensive investigations into robotic brickwork (Figure 1) in 2006 and created a number of architectural demonstrations and building prototypes. These explorations are an important step away from standard brickwork towards enabling highly articulated building elements, where both a novel aesthetic and a functional potential are liberated through the introduction of bespoke assembly operations (Gramazio and Kohler, 2008a). Because the resulting artefacts are robotically constructed, the resulting structures combine the flexibility of individually fabricated, highly customised building parts with the advantages of additive mass production. As such, these brickwork elements can be fabricated without any need for repetition, at low cost and with a constant and controllable quality. The driving force behind this approach is not the mere rationalisation of fabrication as pursued by former approaches during the 1990s (Andres et al., 1994; Pritschow et al., 1994), but the exploration of novel brickwork constructions and their relation to design freedom, structural performance and the robotic assembly itself.

This unique approach to robotic brickwork is particularly explored in projects such as the Gantenbein Vineyard Façade (Bonwetsch, 2015) and the installation Structural Oscillations (Gramazio and Kohler, 2008b), which are presented in the first part of this contribution. Subsequently, we will discuss the industrial transfer of this research to large-scale demonstrations, namely the software tool BrickDesign (Bonwetsch et al., 2012) and its application to the design and fabrication of the façades of the multi-residential building ensemble Le Stelle in Locarno, Switzerland. All these endeavours required many innovations (including the development of novel computational design and construction processes, interfacing seamlessly with automated fabrication procedures) and successfully illustrate the potential of comprehensively automated brickwork assembly processes, fostering profound changes in the design, performance and expression of architecture at building scale.

As shown by the projects discussed in this article, robot-based construction processes are usually distinguished by the large number of elements, very detailed organisation, high degree of definition throughout and a distinctive coherence between the single elements and the whole. Nevertheless, the prospect of using a robot to join simple, basic elements into a complex whole calls for a short discussion of the concept of the ‘generic’ building element (Gramazio et al., 2014). A brick is fundamentally generic because it can be assembled in a number of configurations resulting in very complex and specific building elements. One could also say that although its form is geometrically clearly defined, its assembly logic is weakly determined. In the joining of the bricks, their formal
simplicity allows an enormous degree of freedom — for example, highly articulated and continuous translations or rotations that would not be possible with a building element that constrains the freedom of assembly through a specific form (Figure 2).

The boundaries of this freedom, however, are clearly defined and are all of a physical nature, such as collision, tipping or tilting during the construction process as well as the structural bonding effect among the bricks. In addition, the complexity of the constructive logic increases dramatically as soon as one departs from the rich canon of traditional bonds. This complexity, generated by the diverse dependencies between the single bricks, can be designed and controlled only through algorithms. Whether the brick — today, in the information age — can still be ‘glorified’ as the lowest common denominator of architecture may well be doubted. But one thing is certain: To this day, the brick remains the most ‘generic’ building element of construction — also and especially in digital fabrication with a robot. With regards to assembly, to the extent to which generic elements can be put together into various, highly informed and differentiated architectural assemblages, the application of robotic assembly techniques becomes not only meaningful but indispensable. Conversely, as soon as the individual elements become specific through geometrically prescribed connections, their joining is largely predetermined and constructive freedom becomes limited. The consequence is that sometimes such elements may be put together more easily and perhaps more quickly by hand than with the robot; in these cases, the specific added value of the robot would be reduced to the pure automation of manual work processes.

At the same time, on a technical level, brickwork lends itself particular well to robotic processing, especially as industrial robots were developed mainly for performing handling and assembly tasks and the basic construction process of brickwork consists of the repetitive assembly of discrete parts. The parts assembled are mainly of the same size and material and are of dimension and weight that can easily be handled by a robot (Figure 2). Further, in traditional brickwork, the bricks are merely stacked on top of each other. Thus, the robot is not challenged to assemble complex joints. In fact, the constructive brickwork system developed and presented here substitutes the traditional mortar bond with an adhesive. On one hand, applying adhesive corresponds to automated robotic processing and is a well-known technique in other manufacturing industries such as, for example, the automobile industry. On the other hand, bonding bricks with an adhesive adds a new performance quality to brickwork, in that it can now receive tension forces. Thereby, as shown especially in the Structural Oscillation project, we can realize complex geometries in brickwork structures which otherwise would not be possible or would be possible only through introduction of additional reinforcement (Figure 3-4).

Viewed from this perspective, it becomes clearer why brickwork is a research field par excellence for digital fabrication. In such endeavours, two aspects converge: the inherent ‘genericness’ of the elements used and the generic machinic capabilities of the robot. These are combined to enable specific and differentiated constructive processes that profoundly affect the architectural design and at the same time become thoroughly informed by it (Bonwetsch et al., 2010).
A project that precisely illustrates this approach and has expressed its potential from early on is the Gantenbein Vineyard Façade. This project is pivotal for two reasons: first, it marks a historical break as the first-time architectural application of an industrial robot. Associated with that is the transition from a manually repetitive to a digitally differentiated robotic fabrication process. The brickwork of this façade (Figure 6-7), in which each brick has been individually positioned and aligned, cannot be built by hand: its design is too differentiated; the bricklaying logic of the façade is that is, the highly articulated arrangement of the bricks, their offsets and angles is too complex. Ultimately, its logic is not intuitively comprehensible to the worker during the act of bricklaying. Second, the Gantenbein Vineyard Façade is significant because it points to the question of how digital design can address the architectural capacities made accessible by the robot. The constructive and phenomenological relationship between resolution and transparency, between the brickwork and its visual appearance (Figure 6), between information and material must be brought to equilibrium among a multitude of diverse aesthetic and functional requirements. While such complex materialisation processes cannot be addressed with traditional design methods, they become controllable and freely formable through the medium of computer programming. This inaugurates an entirely new architectural approach that allows for bringing the discipline's fundamental material capacities into equilibrium.

Besides the direct relationship between design and material, programming and construction, the question of the relation of the machine to the entire structure arises. Following the known paradigm of prefabrication, robot and building are initially spatially separated. If instead the entire robotic unit is made transportable as with the mobile robotic unit R-O-B, which was put into operation for the production of Structural Oscillations, Venice 2008 (Figure 8), or Pike Loop, New York 2009 then the situation changes considerably. In such cases, the robot leaves the protected surroundings of the factory and produces directly on the construction site. R-O-B stands for the flexible use of the robot and definitively expands the traditional prefabrication paradigm of the building industry. Housed in a modified standard freight container, the mobile fabrication unit can be deployed all over the world. R-O-B combines the advantages of robot fabrication — manufacturing diversity with consistent precision and production quality — with the advantages of short transport distances and the flexibility of production on the construction site. Thereby we return to the concept of the field factory, which was developed in industrial construction during the 1960s (Langenberg, 2009). The small factories for the serial production of building components that were erected directly on site for large construction projects could not gain a foothold because of the success of industrial prefabrication, which rapidly led to a dense network of factories turning out ready-made components. This resulted in considerably shorter transport distances to the respective construction sites, rendering field factories unprofitable. Today, with R-O-B, a reconceptualisation of this idea appears to be taking place, this time with entirely new possibilities for flexible production, whereby versatile construction procedures can be coordinated with the requirements of the construction site, just-in-time, and industrial quality. In other words, R-O-B is the core of a generic and information-based, and therefore flexible, new edition of the field factory.
Along with the robotic fabrication process, corresponding digital design tools that allow for truly integrated design and fabrication of robotically assembled brickwork are requisite for the successful transfer of this research to the building industry. Due to their limitations in designing with a large number of elements, traditional CAD systems do not qualify as design tools for robotic brickwork processes. In fact, the robotic assembly process demands new design tools. The software tool BrickDesign was developed to address this shortcoming (Bonwetsch et al., 2012). Conceptually, the software is based on the creative control of a large number of units in order to foster a systemic, unifying planning process. In this, BrickDesign allows designing a façade from its constituent elements — the bricks — rather than through an overall geometry (Figure 9). Thereby, the software enables exploration of the full design space spanned by the possibilities of robotic assembly processes. Further, the same data set for the design of the façade can be utilized for execution planning, such as panelising the façade and defining constructive details like anchoring points. Finally, the BrickDesign data is the basis for generating the control code for the robotic system (Figure 9). In this way, the software combines digital design and fabrication into a computational planning tool and implements the non-standard robotic assembly process for brickwork in an integrated architectural planning process. By extending architectural planning and manufacturing methods, BrickDesign creates a new level of robotic use in architecture (Willmann et al., 2012).

A specific case for the industrial implementation of robotic brickwork is presented by the façades of the multi-residential building ensemble Le Stèle. The brick façades are based on an open stretcher bond, although the individual bricks move out of the two-dimensional plane of the façade, creating bossage-like protrusions that are irregularly distributed over the façades (Figure 10). The 3.425 square metre large façade consists of 87,392 bricks and was produced in 707 single non-standard brick panel elements. Like the previous realised experimental projects, due to the number of bricks that need to be individually controlled and the complex relation of their assembly, this façade could not be designed, planned or executed using conventional manual methods. From the early design stage, the façade variants were explored in BrickDesign. The complete planning, up to generating the fabrication data, was handled within the software, thereby realising a digital chain linking the design with the assembly process. Apart from allowing development of the design and execution details in parallel, such an integrated approach allows for a bi-directional information flow. Design and execution are synchronised by controlling each individual brick and assessing brick assemblies both in terms of their visual appearance and their feasibility, such as the maximum protrusion of the individual bricks according to the constraint of a minimum area of overlap between the bricks. Thereby, the design is combined with fabrication thinking, where function and form are negotiated in an informed assembly process. The brickwork is developed out of the logic of its material, construction principles and the tools applied. Ultimately, this holds the potential to leverage new architectural capacities outside the commonly known standards.
In the last decade, a number of promising robotic brickwork processes have been developed, resulting in robust and versatile brickwork constructions. Seen against this background, robotic brickwork has become a mature technology over the last decade, and, overall, has successfully brought forward the topic of digital fabrication as a new field of research in architecture. At the same time, this approach radically expands the spectrum of traditional brickwork and, additionally, introduces robotic fabrication logics to the building construction sector. Therefore, the presented explorations — spanning almost a decade of comprehensive research — represent a radical shift in scale and scope, where non-standard brickwork can be efficiently aggregated from a multitude of discrete elements to foster highly versatile constructions. Here, the realised projects make clear that even the oldest and most tradition-rich prefabricated building element, the brick, cannot elude processing by digital technologies; accordingly, this endeavour also promotes integrative computational design methodologies and techniques, where design decisions orchestrate a multitude of construction and fabrication attributes from the very beginning of the design process onward and up to the different stages of prototyping and final realisation. In order to fully exploit the potentials inherent to a robotic assembly process, its parameters have to be made available at an early design stage. Thereby, parameters of fabrication can inform the process of design exploration. However, the industrial transfer of robotic brickwork is still in its infancy and presents many challenges to architecture and the construction industry. And yet this approach is captivating: It not only creates a new vision for robotic construction in architecture but also emphasises new possibilities for the exploration of its real-world implementation — revitalising architecture’s constructive nature and engaging with its own material roots.

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